Chapter

Perspective Chapter: Smart Liquid Cooling Solutions for Advanced Microelectronic Systems

Montse Vilarrubí

Abstract

Thermal management is today a primary focus in the electronics industry due to the continuous increase of power density in chips increasingly smaller in size, which has become a critical issue in fast-growing industries such as data centers. As air-cooling fails to meet the high heat extraction demands of this sector, liquid cooling emerges as a promising alternative. Nevertheless, advanced microelectronic components require a cooling system that not only reduces the energetic consumption but also enhances the thermal performance by minimizing the thermal resistance and ensuring high-temperature uniformities, especially under variable heat load scenarios with high heat dissipating hotspot regions, where conventional liquid cooling solutions prove inefficient. This chapter provides an overview of different passive heat transfer enhancement techniques of micro heat sinks from the literature, focusing on intelligent and adaptive solutions designed to optimize the cooling performance based on local and instantaneous cooling requirements for non-uniform and time-dependent power distribution maps.

Keywords: liquid cooling, electronics thermal management, adaptive cooling, heat transfer enhancement, micro heat sinks, variable hotspots, energy efficiency

1. Introduction

Moore's law, formulated in 1975, projected that the number of transistors in a compact integrated circuit (IC) would double every 24 months. Over the past few decades, the progress in circuit density has closely matched this prediction [1]. At the same time, Dennard scaling law stated that as transistors shrink in size, their power density remains constant. However, in recent years, this law seems broken as the performance enhancement slowed down while the number of transistors per circuit is still increasing [2]. As a result, the continuous increment in power density of ever smaller ICs has led to an exponential rise in heat dissipation, and thermal management emerged as a primary concern for the industry [3].

Additionally, the escalating demand for data processing, networking, or data storage systems has led to a big expansion of the data center industry, which presently contributes to 1–1.5% of global electricity consumption, with CO_2 emissions equivalent to those generated by the airline industry and has an estimated growth of 500% by 2030 [4–6].

To ensure the temperature of the IT equipment remains within its safe operational range, data centers need effective cooling mechanisms in place, which traditionally involved the use of large cooling Heating, Ventilation, and Air Conditioning (HVAC) systems. Then, within a data center facility, the cooling system stands out as one of the most energy-intensive components, accounting for 30–40% of the total energy consumption (**Figure 1**) [7].

Until recently, air-based solutions, including passive methods relying on natural convection or active cooling involving fans or heat sinks, were extensively employed for electronic component cooling. However, with the increasing heat dissipation demands of advanced microelectronic systems, conventional air cooling mechanisms are insufficient to provide the needed heat removal capacity, and water-based systems become preferred [9, 10].

Since Tuckerman and Pease [11] demonstrated the viability of microchannels liquid cooling for electronic chips back in 1981, this technology has been subject to extensive research to improve its performance, including geometric modifications [12, 13], the use of nanofluids or the study of alternative technologies such as heat pipes, jet impingement, or spray cooling [14, 15]. Although this technology achieved low thermal resistances, it still has the challenges of poor temperature uniformities, which can result in serious damage to the performance and reliability of the chips [16], and large pressure drops, which result in more energy-demanding cooling devices due to higher pumping power.

Advanced microelectronic components, such as multicore processors or three-dimensional integrated circuits (3D-ICs) are currently being persuaded by the IC industry due to their high performance and low power consumption [17]. Multicore processors are based on multiple independent execution cores on a single CPU that can work in parallel tasks, where each core dissipates multiple times the heat flux dissipated at the rest of the chip, which leads to the appearance of hotspot regions and non-uniform power map distributions [18–20]. Similarly, 3D-ICs architectures stack multiple dies, interconnected through vertical connectors to extend the performance

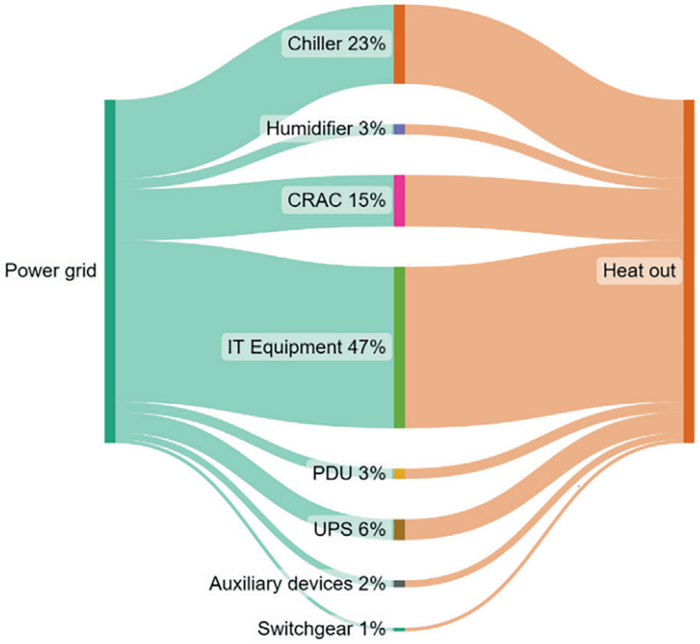

Figure 1.
Sankey diagram showing the average power consumption of the different components of a data center [8].

of 2D chips [9]. Here, thermal management becomes critical as the heat-generating layers are aligned in adjacent films creating localized hotspots, and any dissimilarity between power maps of individual chips constituting the stack would add another geometrical dimension to the thermal non-uniformity [21, 22].

Hotspot regions can dissipate multiple times the heat flux dissipated at the rest of the chip, requiring high flow rates for effective cooling. Nevertheless, as these regions are typically localized, maintaining constant large flow rates across all cooled devices can result in overcooled systems. Various attempts implementing single-phase liquid cooling have been made to redirect the coolant to the most demanding zones while reducing the required pumping power [23–25]. For example, some authors proposed the use of a cold plate with variable microchannel width or pin-fin density to effectively dissipate high heat fluxes from small areas and achieved reduced thermal gradients at the package level with low-pressure drop, especially when combining this system with a central inlet and two side outlets [26–30]. In a different line, Lu et al. [31] proposed the use of fixed vortex generators along the height of a rectangular microchannel, placed upstream of the hotspot region, and their numerical results indicated that the adoption of these flow disruptive elements can significantly improve the cooling effect over the hotspot with a lower pressure loss penalty compared with plain channels. Other authors followed the same research line with different degrees of success [32, 33]. However, all previous detailed systems rely on fixed geometries and lack the ability to adapt their behavior to changing heat load scenarios across time and space, so these systems are only optimized for specific conditions, leading to oversized pumping powers and poor temperature uniformities for varying operational parameters.

Consequently, advanced cooling solutions that aim to improve the performance of current microelectronics systems should focus on devices capable of dynamically adapting to changing boundary conditions across time and space. These solutions should simultaneously strive for reduced energy consumption and improved thermal performance, with reduced thermal resistances and high-temperature uniformity.

2. Overview of passive heat transfer enhancement techniques in micro heat sinks (MHS)

Different heat transfer enhancement techniques have been explored in the literature to improve the cooling capabilities of microscale heat exchangers and overcome their limitations. Tao et al. [34] identified three different mechanisms to improve the thermal transfer: reducing the thermal boundary layer, introducing flow interruptions along the flow path, and enhancing the velocity gradient near the heated surface. Among the common passive heat transfer enhancement methods, which do not require external energy use, are channel shape modifications, surface roughness adjustments, incorporation of fluid additives, and the addition of flow disruption elements inside the channel [35, 36].

2.1 Modification of channel shape

Several researchers have demonstrated that curved flow paths can enhance heat transfer by generating secondary flows and Dean vortices [37]. Accordingly, various studies have evaluated the thermal performance improvements of the microchannel heat sink (MCHS) with curved walls, concluding that the generation of vortices in the channel cross-sections promotes convective heat transfer (**Figure 2**) [38–40].

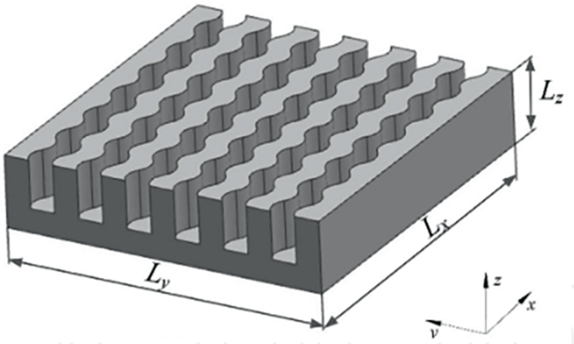

Figure 2.
Schematic of a wavy microchannel heat sink [39].

Additionally, the incorporation of superhydrophobic walls has shown significant potential to reduce the pressure drop of the cooling devices [41].

The effect of cross-sectional channel aspect ratio and shape have been found to have a significant influence on the heat transfer and fluid flow characteristics of the MCHS [42, 43]. For example, Wang et al. [44] investigated the effects of different channel shapes on the heat transfer and fluid flow characteristics of a microchannel and observed that rectangle channels exhibited better overall performance than other shapes but also had lower thermal resistances. Other researchers have focused on the generation of secondary flows, which can lead to significant thermal enhancement but with an added pressure drop penalty [45, 46]. However, the combination of ribs and secondary channels has been shown to further enhance mixing while reducing pressure drop [47]. In a different line, various researchers have evaluated the heat transfer enhancement in double-layered microchannel heat sinks (DL-MCHS), which exhibited lower temperature rise and pressure drop compared to conventional MCHS (**Figure 3**) [48–50]. Also, the use of porous surfaces attracted the attention of researchers to improve thermal performance with reduced pressure drops, both in single-layer and double-layer MCHS [52, 53].

2.2 Surface roughness

Another passive thermal enhancement technique discussed in the literature involves modifying the characteristics of the heated surface through variations in surface roughness. This approach has been found to increase the flow resistance and improve heat transfer [54–57]. For instance, Gamrat et al. [54] presented a model

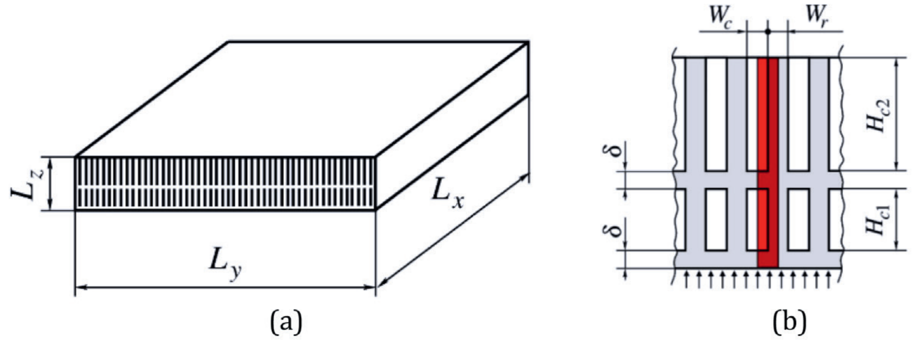

Figure 3.
Parallel double-layered microchannel heat sink: 3D-view (a) and cross-section view (b) [51].

in which roughness was modeled as a pattern of parallelepiped elements distributed periodically within microchannels. They studied the influence of roughness on heat transfer in laminar flows and introduces a relative roughness value (k*) able to provide thermal performance values higher than one. More recently, Madev and Manay [57] conducted experimental evaluations to study the effect of induced surface roughness on multiple stainless-steel microchannels and revealed a notable impact on mixed convective heat transfer, which decreased with the augmentation of the hydraulic diameter of the channel.

2.3 Fluid additives

The addition of solid nanoparticles into the working fluid has been investigated by different researchers as a promising method to enhance heat transfer [58, 59]. Also, various studies explored the combination of nanofluids with improvements in geometrical parameters of the heat sink, such as the use of vortex generators [60], ribs and grooves [61, 62], pin fins [63], or jet impingement [64]. For example, Heydari et al. [61] assessed the effect of combining triangular ribs inside an MCHS with different nanofluids and concluded that an increase in the volume fraction of nanoparticles, as well as the use of nanoparticles with smaller diameters, lead to greater heat transfer. The authors also observed that the friction coefficient and pumping power remained nearly independent of nanoparticle diameter. On the other hand, Alkasmoul et al. [65] evaluated the thermohydraulic performance and feasibility of various nanofluid types and concentrations in an MCHS. Their results stated that the effect of increasing flow rate had a more dominant effect than increasing nanoparticle concentrations, while at the same time, all nanofluids required higher pumping power than pure water at all concentrations (**Figure 4**).

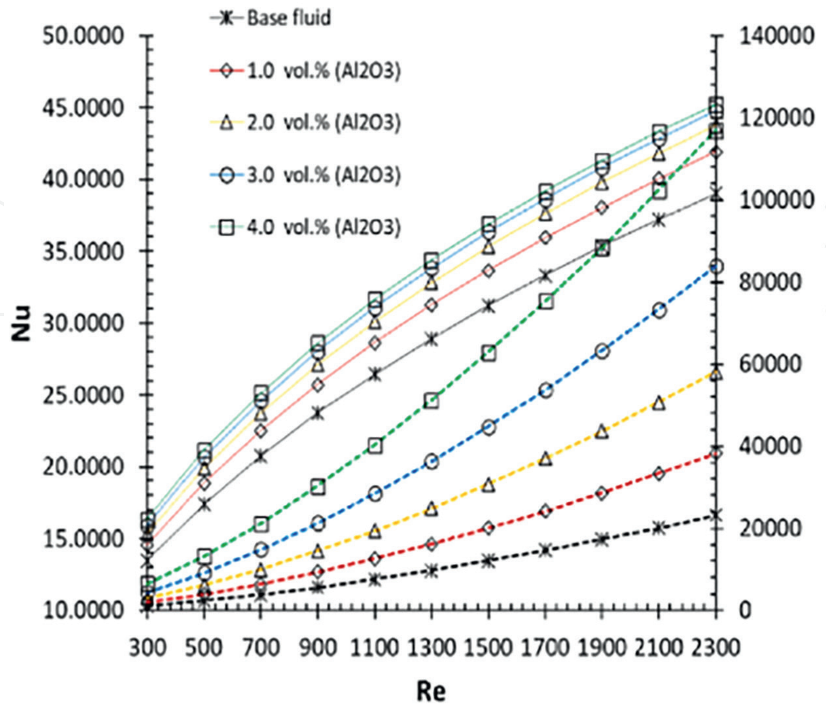

Figure 4.
Nusselt number (solid line) and pressure drop (dashed line) in an MCHS at different Reynolds numbers for water and various concentrations of nanofluid [65].

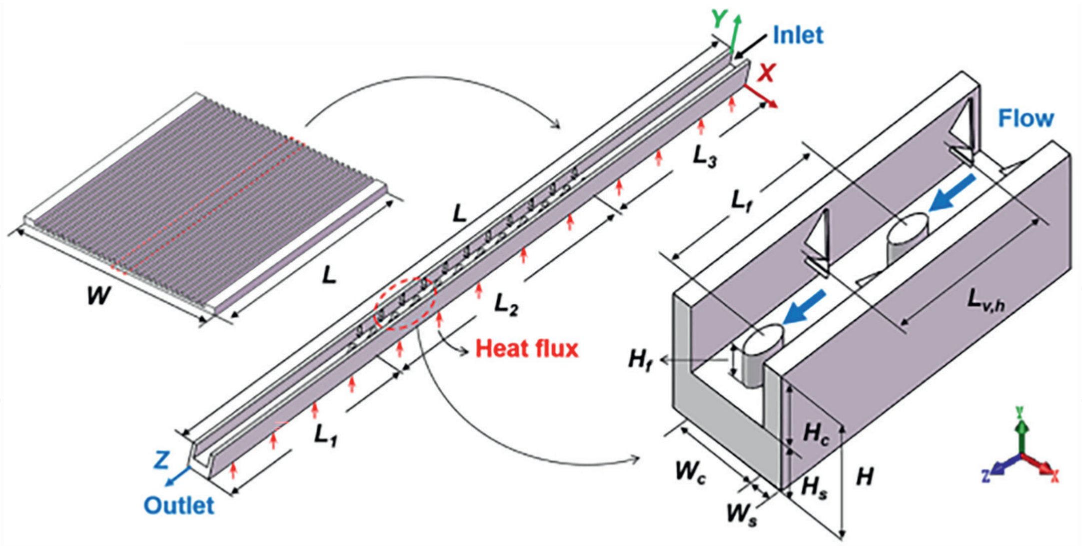

Figure 5.
Schematic diagram of an microchannel heat sink with pin fins and vortex generators acting as flow-disturbing elements.

2.4 Flow disruption

A widely employed technique for thermal enhancement involves the incorporation of flow interruptions within the channel flow. These interruptions disrupt the flow field and the growth of the boundary layer and induce fluid swirling along the cooling channel, leading to better mixing and redevelopment of this layer, which results in lower thermal resistance [66]. The different disturbing elements used for heat transfer enhancement are based on sidewall obstructions, such as ribs and cavities [67], or flow obstructions like wings, winglets [68], ribs [69], pin fins [70], or surface protrusions (**Figure 5**) [71]. However, the overall performance enhancement of an MHS when using VGs depends on many geometric parameters such as their shape, dimensions, position, or angle of attack [60].

2.5 Current limitations

Although passive heat transfer techniques have been demonstrated to provide extended cooling capacity to microscale heat exchangers, they also induce additional hydraulic resistance at the flow pass, which leads to higher pressure drops and pumping power on a continuous basis. Furthermore, these systems are typically designed to handle the worst-case situation and lack adaptability to varying time-dependent and non-uniform power distribution scenarios, which leads to overcooling when the heat extraction demands are not maximized. To address these challenges, there is a need for more intelligent and adaptive cooling solutions that can dynamically respond to changing heat load conditions and optimize cooling performance while minimizing unnecessary energy consumption.

3. Smart heat transfer enhancement techniques in MHS

In last years, smart cooling solutions started to focus on the performance optimization of MHS when submitted to changing boundary conditions in time and space, as the ones induced by advanced electronic systems such as multicore processors, SoC, or 3D-ICs. In these cases, the cooling systems should be able to maximize their thermal performance to high heat extraction demands at peak points while minimizing the energetic consumption when the cooling demands decrease. Therefore, low thermal resistances, high-temperature uniformities, and reduced pumping power are the main goals to achieve under variable power scenarios both in time and space.

3.1 Flow rate regulation

Different studies suggested employing different actuators as valves to enable local flow rate regulation at the different regions of the cold plate based on the instantaneous cooling requirements. This intelligent regulation allows the redirection of more flow to the hotspot regions, achieving a more uniform temperature profile at the cooled device, effectively optimized for any variable thermal load scenario. However, the addition of valves inside the cold plate results in an increment of the pressure drop and so, higher energetic requirements when the valves are in the closed position.

For example, Azarkish et al. [72] analytically investigated the thermal response of temperature-regulated microvalves able to adapt the coolant mass flow rate distribution based on the local chip temperature. Linear and exponential responses of the microvalve were evaluated, obtaining in both cases a significant reduction in mass flow rate, while temperature uniformity across the chip was significantly improved with exponential microvalves. Similarly, Amnache et al. [73] detailed the fabrication process flow of Ag non-linear doubly clamped beams to implement an array of self-adaptive valves in a liquid-cooled heat sink. The fabrication was successfully done in a clean room through a lithography process. Following the same research line, Laguna et al. [74] experimentally evaluated the potential of a microfluidic cells cooling system, where each cell integrates a self-adaptive microvalve capable of tailoring the flow rate to the local and instantaneous cooling needs. The performance of this cooling system was assessed and compared with regular microchannels under variable heat loads. The results indicated a maximum temperature reduction of 15°C and a 74.7% decrease in pumping power when implementing the self-adaptive flow rate control. These findings highlight the potential of this cooling solution as a promising configuration for local and instantaneous thermal management control.

With a different working principle, other authors took advantage of the intrinsic shape memory effect of shape memory alloys (SMA) to develop thermally adaptive valves. Waddell et al. [75] employed SMAs as microfluidic valves inside a cooling channel to regulate the flow disturbance and enhance the local heat transfer performance and, although the combination of MCHS with SMA exhibits good performance in cooling hotspots, authors concluded that this solution could not be applied in practical large-scale industry due to its high cost. More recently, Vilarrubí et al. [76] studied the use of an array of bimorph SMA/metallic valves inside the cooling channels of a liquid-cooled cold plate designed for a rack server. The work demonstrated the capacity of these valves to double the flow rate at each channel for high cooling demands, resulting in energy savings of up to 30%. However, the authors also highlighted the challenges associated with this material due to its intrinsic thermal hysteresis cycle when operating outside its full phase transformation range, which limits the implementation of the solution (**Figure 6**).

Another approach of interest is the use of soft materials for a thermally responsive flow control, based on polymer gel-type materials. In this case, when the temperature of the hydrogel is lower than a determined temperature, the polymer chains inside

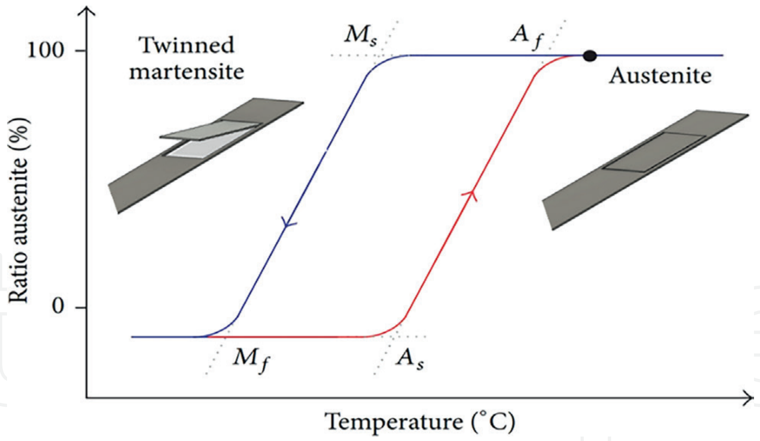

Figure 6.
Crystallographic behavior of SMA valves in function of its temperature. A_s *refers to the starting temperature of the austenite phase transformation,* A_f *to the finishing temperature of the same phase,* M_s *is the starting temperature of the martensite phase and* M_f *the finishing temperature of the same phase transformation [76].*

the hydrogel are hydrated and its volume increase dramatically. Contrarily, if the hydrogel temperature increases over a certain limit, the polymers begin to collapse and contract suddenly, so the volume decreases greatly in a short time. The main benefits of this technology include a quick thermal response with significant volume changes, easier fabrication with complex shapes, and low cost. Tudor et al. [77] reported the synthesis, characterization, and performance of thermo-responsive hydrogels as temperature-controlled actuators within microfluidic devices, where the hydrogel size was modulated by localized changes in its temperature due to the lower critical solution temperature behavior exhibited by the hydrogel. The same principle was studied by Yan et al. [78] to automatically regulate the mass flow rate distribution in a fractal microchannel heat sink when submitted to random hotspots. The authors stated that the swollen volume could reach 50–80 times the contracted volume and numerically demonstrated a reduction of 4.47°C in the maximum temperature rise of the heat sink when using hydrogels as valves. However, they observed that extreme hotspot conditions lead to worse uniform cooling as all hydrogels are in the same state. Also, Li and Xuan [79] proposed an embedded cooling system of a microchannel/pin fin heat sink with thermo-sensitive hydrogels located at the outlet channel. The obtained results demonstrated that heat flux of up to 500 W/cm^2 could be dissipated, with a pressure drop of 34.0 kPa and a reduction of peak temperature of 12.2°C, due to the studied self-adaptive cooling. The same authors also proposed the integration of hydrogel valves in silicon manifold channels and evaluated its impact on various hydrogel compositions. In this case, random hotspots of 460 W/cm^2 were effectively removed with a flow rate of 0.87 mL/s, and surface temperature uniformity was reduced to 27.2°C, achieving effective adaptive cooling of random hotspots [80].

Other works focused on developing external control mechanisms for flow rate adjustments, to match the instantaneous cooling requirements and achieve significant pumping power savings. For instance, Zhang et al. [81] developed an adaptive control law for the thermal-fluidic control of a microchannel evaporator, which estimated the heat transfer coefficient and adjusted the flow rate accordingly. Also, Da Luz et al. [82] proposed to adapt the pumping conditions to provide the minimum flow rate required to maintain the maximum chip temperature, through a variable flow miniaturized pump system with an associated electronics drive (**Figure 7**). Recently, Shahi et al. [83] explored the implementation of active flow control at the server level

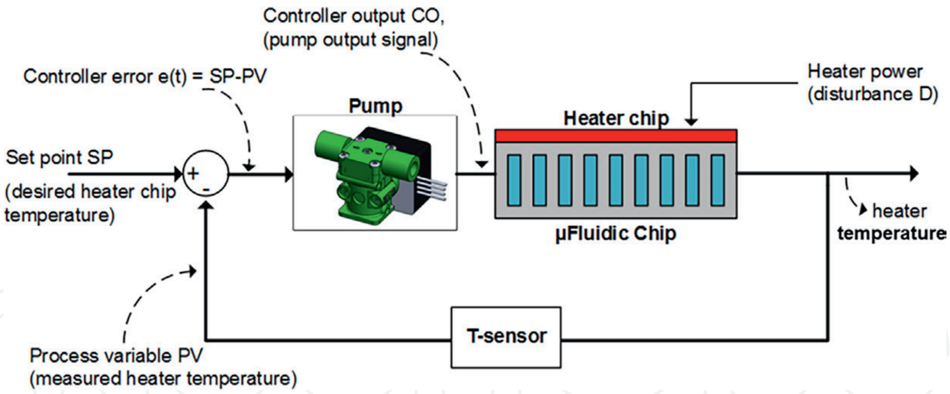

Figure 7.
Simplified schematic of the control loop block diagram for external control of the flow rate in function of the maximum cold plate temperature [82].

to regulate the coolant flow rates. They employed a ball valve connected to a micro engine to control the valve position via predefined rotational angles. While these strategies can adapt the overall flow rate of the cooled device, they may not efficiently regulate conditions for variable heat loads inside the same cold plate, which could turn in the overcooling of background areas and poor temperature uniformity. Thus, it could be a useful approach to combine with other adaptive solutions placed inside the cold plate.

3.2 Heat transfer regulation through flow disruption of fluid boundary layers

The effectiveness of different flow disruption techniques in enhancing the heat transfer within a MHS has been well established. However, their lack of adaptability to variable power scenarios results in oversized pumping powers and unnecessary energy consumption. To overcome this drawback, some researchers proposed to optimize the heat transfer capacity of the cooled device through the addition of smart mechanisms able to disrupt the fluid boundary layer and increase the mixing within the cooling channel when the applied heat loads vary in time and space. In these cases, the heat transfer enhancement capabilities of the flow-disturbing elements are only applied at high heat loads, remaining in a neutral position otherwise to minimize the pressure drop along the channels.

In 2001, Champagne and Bergles [84] introduced a novel concept involving a variable roughness heat exchanger tube based on SMA wire coils and experimentally assessed the heat transfer enhancement and pressure drop for this self-adaptive system. In a similar way, Aris et al. [85] later investigated the effectiveness of SMA delta wings acting as VGs for convective cooling, using air as working fluid, and demonstrated their impact on heat transfer enhancement. Within liquid cooling, Vilarrubí et al. [86] evaluated the impact of an SMA wing, trained through a Two-Way Shape Memory Effect, on the thermal resistance of a water channel. Their experimental results showcased a reduction in the thermal resistance between 57% and 63%, which was more significant at higher flow rates where the effect of the vortex generators became more noticeable. Additionally, the study highlighted the ability of adaptive SMA wings to maintain a uniform surface temperature even as heat flux increased, obtaining a surface temperature gradient of 7°C for a heat flux variation of 34.2 W/cm^2 (**Figure 8**). Later, Regany et al. [87] experimentally assessed the thermal improvement capacity of an array of SMA adaptive fins inside a liquid

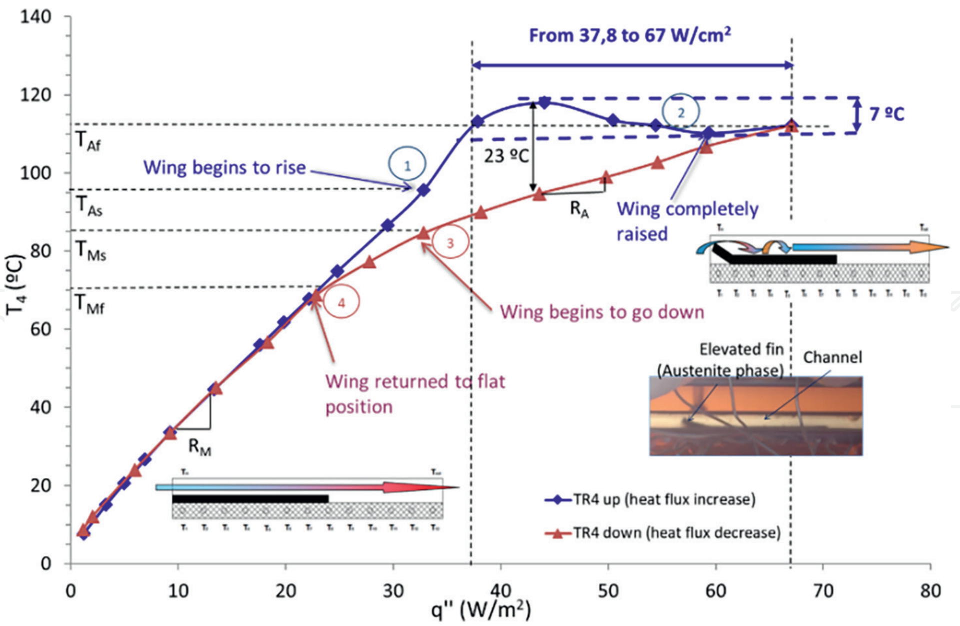

Figure 8.
Surface temperature evolution for varying heat flux due to the adaptive use of an SMA wing [86].

cooling channel, and demonstrated enhancements of 63% in the temperature uniformity and 50% in heat transfer increment due to the implementation of the adaptive fins (**Figure 9**). At the same time, Chu et al. [88] investigated the application of an SMA coil as an adaptive vortex generator to alter the flow characteristics of a microchannel heat exchanger, allowing to increase the Nusselt number by 112% at a heat flux of 1×10^5 W/m^2. Furthermore, the authors subsequently proposed employing graded SMA coils to intelligently recognize the location of hotspots and experimentally demonstrated better overall performance with this improved system to address random hotspots [89].

Adhering to the same working principle but using a different mechanism, Vilarrubí et al. [90] introduced the use of doubly clamped beams with eccentricity as passive thermal actuators, to act as adaptive vortex generators inside a MCHS. At a certain temperature, these beams would buckle, thereby disrupting the boundary layer of the channel and enhancing its thermal resistance. For a given thermal load variable in time and space, the authors computed a pumping power reduction of 8% in the cooling system (**Figure 10**). Subsequently, the same authors developed a system of self-adaptive passive thermal vortex generators based on bimetallic fins that could adjust their shape with temperature fluctuations (**Figure 11**). This innovative system allows the optimization of the cold plate thermal capacity for any variable heat load

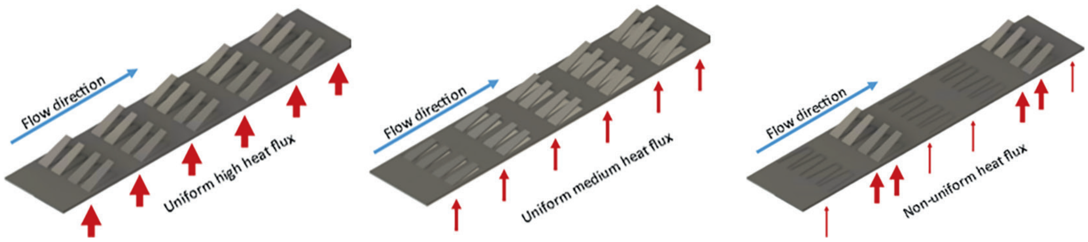

Figure 9.
Working principle of the SMA self-adaptive fins placed inside a liquid cooling channel and acting as vortex generators [87].

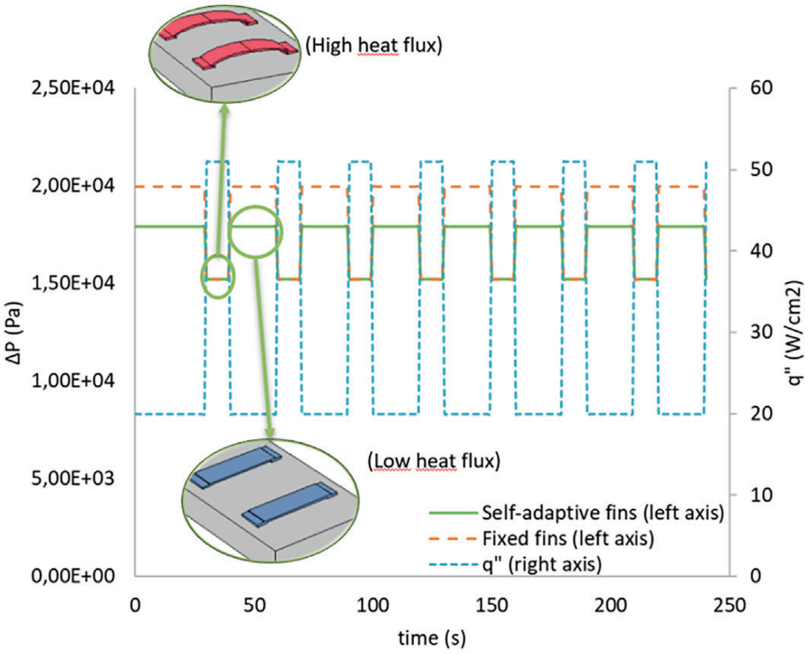

Figure 10.
Comparison of pressure drops along a microchannel with adaptive and fixed doubly clamped beams acting as vortex generators [90].

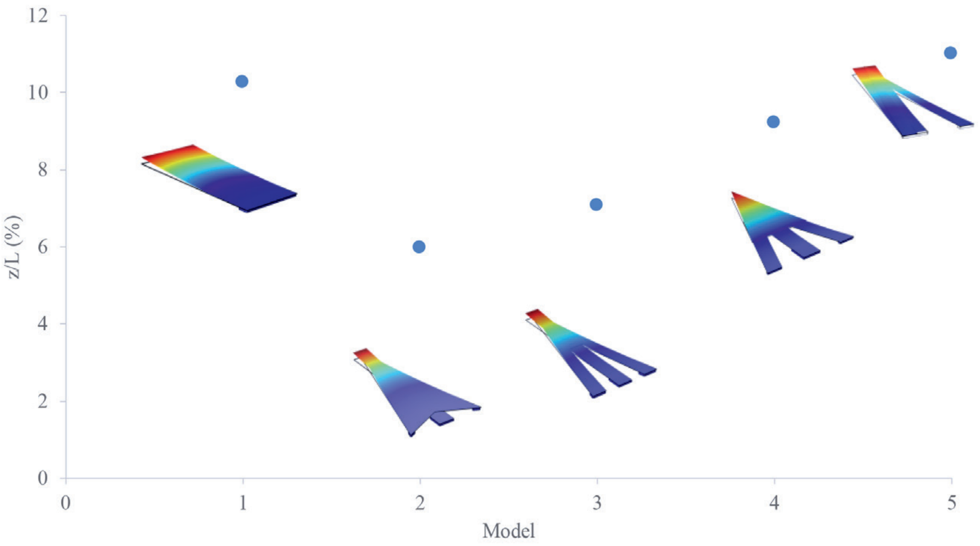

Figure 11.
Vertical displacement (in % of the fin length) reached by different structures of bimetallic adaptive fins [91].

scenario while reducing the energy requirements of the cooling system. The numerical results of this study revealed a heat transfer improvement of up to 40% in a MCHS due to the implementation of the fins and a pumping power reduction of 34% for a specific heat load scenario when compared to a non-adaptive system [91].

Apart from the previously cited works that can adapt their shape based on temperature, there are other research lines involving the use of active actuators to enhance the thermal capacity of cooling systems. For example, Lambert and Pangel [92] proposed employing thin elastic flaps externally actuated to enhance fluid mixing in a microchannel. Their results showed that larger flap displacements resulted in higher mixing fractions, and the addition of multiple flaps further

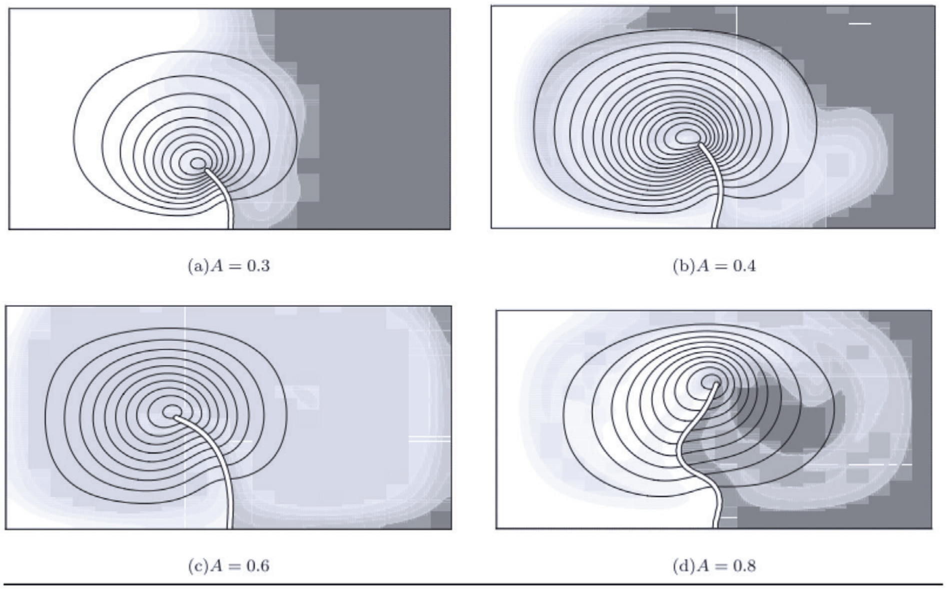

Figure 12.
Streamlines and concentration contours for different aspect ratios of flap length and height of the elastic flap externally actuated [92].

improved mixing (**Figure 12**). Similarly, Mirzaee et al. [93] conducted numerical simulations of a 2D channel with an oscillation-controlled flap, comparing the thermal performances between a flexible and a rigid flap. The findings indicated that the flexible flat not only increased the thermal performance but also led to lower pressure drops compared to the use of rigid flaps. Separately, Fang et al. [94] developed an active heat transfer solution using an array of synthetic jets that generated periodic disturbances when interacting with microchannel flow. The local turbulence created by the jet near the heated channel wall disrupted the thermal boundary layer, resulting in a 130% enhancement in heat transfer with a small increase in pressure drop.

3.3 Other methods

Other methods developed in the literature for efficiently cooling variable heat loads include thermoelectric coolers (TECs), electrowetting, parallel microchannel distributions, two-phase cooling, and the prediction of the thermal map.

TECs have garnered attention as an active cooling method for electronics in recent years. Based on the Peltier effect, TECs can directly transfer electricity to the temperature difference with no moving parts, fast thermal response, silence, and reliability [95]. Although TECs are commonly used with air-cooled heat sinks, some researchers explored their potential in combination with liquid-cooled systems to efficiently manage hotspots. For instance, Hao et al. [96] proposed a hotspot mitigation equipment that integrated TECs with a mini-channel heat sink. Their results showed a decrease in the hotspot temperature of 3.1°C when the R_{th} was 0.6 K/W.

As an alternative approach, some authors evaluated the potential of using the electrowetting phenomenon in microelectronics cooling, employing an array of liquid droplets that can be independently moved along the surface. While originally developed for biological and chemical lab-on-chip applications, this technology has shown its applicability as an adaptive cooling platform for microelectronics. Paik et al. [97] presented an innovative chip cooling technique based on a “digital microfluidic” platform, showcasing the ability to program droplets to cool hotspots in both closed and open systems. Later, other researchers delved into the potential of electrowetting-on-dielectric (EWOD) digital microfluidic devices to create adaptive cooling solutions for non-uniform and transient heat load scenarios [98–100].

Alternatively, Farnam et al. [101] developed a 3D numerical model to assess the thermal behavior of an entire microchannel heat sink coupled with a microprocessor, considering two-way fluid flow under variable heat load scenarios in both time and space. The obtained results revealed that the implementation of a two-way fluid flow could decrease temperature gradients in the device, particularly when hotspots were located downstream in a one-way fluid flow application. These findings highlight the potential for implementing a smart sink capable of adjusting flow direction as needed to control thermal gradients. Furthermore, Ansari and Kim [102] analyzed the thermal performance of double-layer microchannel heat sinks (DL-MCHS) under random hotspots and stated that the cross-channel design of DL-MCHS exhibited the lowest thermal resistance and minimum temperature variation among the hotspots (**Figure 13**). In a different study, Maganti et al. [103] experimentally evaluated the use of various configurations of parallel microchannels coupled with nanofluids to efficiently cool non-uniform heat loads based on different hotspot distributions. Nanofluids were employed as a smart cooling system to efficiently cool hotspots due to the nanoparticle slip mechanisms.

In 2003, Mukherhee and Mudawar [104] demonstrated a smart pumpless loop capable of enhancing its cooling capacity by increasing the velocity of a two-phase mixture along the boiling surface when an increase in the heat flux was detected. Although two-phase cooling for hotspot mitigation has garnered significant interest in recent years, the instabilities associated with this technology have made it challenging to apply on a large scale up to the present time [105].

In a separate approach, Chauhan et al. [106] proposed to address the design of microprocessors to mitigate hotspots, as the placement and arrangement of different electronic components can influence their thermal behavior. The device was cooled using single-phase MCHS using water as the coolant. The study demonstrated that the efficiency of the MCHS was maximized when the higher heat flux components were placed at inlets, hence, an efficient installation of the MCHS proved highly effective in bringing down the maximum hotspot temperature to 72.1°C and limiting the temperature of the remaining areas of the chip to 55°C.

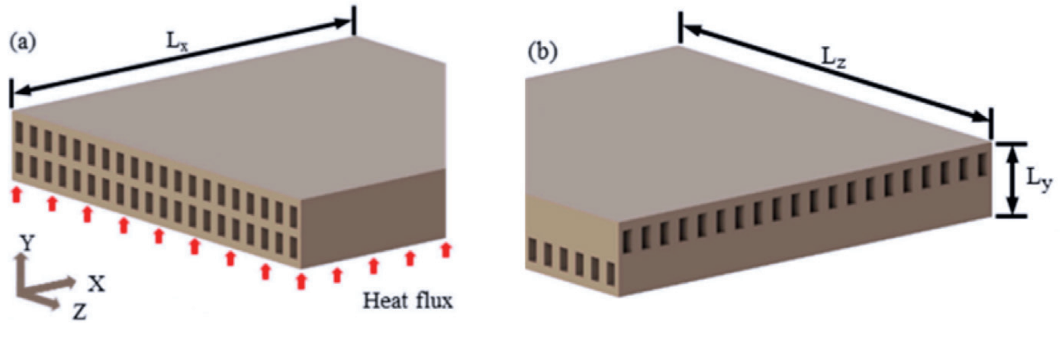

Figure 13.
Schematic diagram of two double-layer microchannel heat sinks in parallel (a) and crossed (b) configurations [102].

4. Conclusions

This chapter summarized different heat transfer enhancement techniques employed to improve the performance of micro heat sinks and overcome their limitations, focusing on intelligent and adaptive solutions that optimize cooling efficiency based on local and instantaneous cooling needs for non-uniform and time-dependent power distribution maps.

Current advanced microelectronic systems exhibit highly non-uniform heat load scenarios, resulting in the appearance of critical hotspot regions that require efficient thermal management. These hotspot regions, typically localized, can dissipate significantly more heat than the rest of the chip, but constant large flow rates across all cooled devices can result in overcooled systems. Moreover, the inability of fixed systems to adapt their behavior to changing heat load scenarios results in oversized pumping powers and poor temperature uniformity for varying operational parameters. To tackle these challenges, advanced cooling solutions that aim to improve the performance of current microelectronics systems must be capable of dynamically adapting to changing boundary conditions across time and space. These solutions should aim for reduced energy consumption and improved thermal performance, with lower thermal resistances and high-temperature uniformity, to obtain efficient and optimized cooling systems under variable conditions.

Recent developments in smart cooling solutions have focused on optimizing the performance of micro heat sinks under varying boundary conditions. Such cooling systems should be able to maximize their thermal performance during peak heat extraction demands while minimizing energy consumption during periods of lower cooling demands. Also, these systems must consider their reliability, since they usually incorporate moving parts that can be more prone to fatigue and wear.

However, the current technology for thermal management of hotspots, especially automatically adaptive cooling, is not fully mature. Thus, there is an urgent need for effective and economical processes to cool random hotspots. In the future, the development of temperature-sensitive materials with better physical performance, lower costs, reliability, and mass production may offer an effective and practical solution for hotspot thermal management.

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Conflict of interest

The author declares no conflict of interest.

Author details

Montse Vilarrubí*[1,2]

1 Universitat de Lleida, Lleida, Spain

2 Universal Smart Cooling S.L., Spain

*Address all correspondence to: montse.vilarrubi@udl.cat

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